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12 ABSTRACT <p>Underwater signal-detection performance of sea lions was influenced by changes in the probability of signal presentation in both acoustic and visual tasks. Normally, marine mammals in a signal-detection task maintain a low level of false alarms while attempting to maximize their correct detections or hits. In the present series of experiments, it was shown that such an objective in a marine mammal (the California sea lion) can be changed without, in some instances, changing the animal's sensitivity. Thus, by changing its response criterion as a function of varying the probability of signal presentation, a set of probability limits could be induced into a sea lion regarding the acceptance or rejection of signal presence or signal difference. By relating the probability of hits to false alarms for several signals of varying magnitude, one can plot the "receiver-operating-characteristic" (ROC) curves for sea lions.</p> <p>Without knowledge of an ROC curve, it is unsafe to assume that the ratio of signal trials to catch trials should be any less than 5:5 (<u>a priori</u> probability = 0.50) when testing the sensitivity of a marine mammal. In addition, it is imperative to take into consideration not only correct reports of a signal's presence (hits), but also the rate of false alarms.</p>	

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OBJECTIVES

- (1) To systematically explore variables affecting the detection of underwater acoustic and visual signals by the California sea lion (Zalophus californianus).
- (2) To determine the degree to which sea lions can vary their response criterion in reporting (by means of an underwater vocal response) the presence of an acoustical or visual signal.
- (3) To determine whether sea lions can acquire a given set of probability limits for the detection of signal presence.
- (4) To explore the effect of the interaction of signal strength and signal presentation probability (a priori probability) on the detection probability and false alarm rate by sea lions.

SUMMARY OF EXPERIMENTS

The following is a description of the experiments conducted during the period covered by this contract—January 1, 1971 through December 31, 1971. Detailed information on research that provides a background for the present experiments (partially supported by previous ONR contracts and by contracts and grants from the Navy Undersea Research and Development Center and the National Science Foundation) may be found in articles published or reported at professional meetings just prior to, during, or soon after the period covered by the present contract. These are listed in the "Current Publications" section.

Background

Quantitative laboratory research has clearly demonstrated that the underwater hearing and vision of all pinniped and cetacean species thus far investigated are far more acute and sensitive than those of man.

(see Schusterman, in press, for a review). Interest has been generated, both from the standpoint that experimental data obtained from these marine mammals may aid in the development of mechanical and electronic devices to facilitate man's underwater sensory perception, and with a view toward training these intelligent animals to act as a searcher, observer, guide and messenger in aiding man in undersea explorations.

When marine mammals are well trained for acoustic detection tasks, either in order to determine the limits of their sensory capabilities or to perform in the field, they will indicate by some behavior ("Yes" or "No") as to whether they can distinguish the signal from the "background noise." During any given period of time, i.e., on any trial, there are four possible contingencies in a signal detection task:

- (1) A signal is presented with the background noise; the animal responds "Yes" and receives a payoff (hit).
- (2) A signal is presented with the background noise; the animal responds "No" and does not receive a payoff (miss).
- (3) Only noise occurs during a given period of time (catch trial); the animal responds "Yes" and does not receive a payoff (false alarm).
- (4) A catch trial is presented; the animal responds "No" and receives a payoff (correct rejection).

A marine mammal's decision-making behavior in a detection task is influenced by variables related to energy levels of stimulus parameters or parameters associated with the animal's sensory apparatus, i.e., variables effecting the individual's sensitivity. However, other variables are also important, e.g., knowledge about the likelihood that certain signals will appear (ratio of signal to catch trials or a priori probability), the gains and losses associated with responses, etc. A variety of marine mammals tested in a variety of acoustic detection tasks, including echolocation, use a high response criterion, i.e., they make conservative decisions regarding the presence of a variety of acoustic signals (Schusterman, in preparation).

On a typical signal detection experiment with humans, one studies the effects on false alarms and hits caused by variations, for example, in the a priori probabilities of signal presentation. When this is done and signal strength remains constant, criterial functions are generated relating the probability of hits to false alarms. This curve is called a receiver-operating characteristic (ROC) and is characterized by a theoretical parameter that is assumed to remain invariant at a fixed signal strength. This parameter in the theory of signal detection (Green and Scts, 1965) is called d' and is measured in normal deviates or standard deviation units between the means of two hypothesized overlapping normal curves of equal variance, one representing noise (n) (internal or external) and the other representing the signal (sn). Thus d' is an index of detectability assumed to be independent of non-sensory factors, thereby yielding a measure of sensitivity that does not depend on changes in the response criteria of the animal. The notion of a "threshold" per se is nonexistent, and sources of control over an animal's responding can be partitioned into sensory and non-sensory or response criterion variables.

The purpose of these first experiments was to explore the interaction of signal strength and a priori probability of signal presentation as it affects the hit and false alarm rates of two sea lions—one in an auditory sensitivity task and the other in a visual acuity task.

Methods

The training and testing conditions, as well as the equipment, have been fully described for both the acoustic and visual tasks (Schusterman, 1972; Schusterman et al., 1972). A lead zirconate titanate transducer (F-41) was used to project a 48-kHz tone into the testing tank for the acoustic task. This high frequency tone was initially chosen because when acoustic testing was begun, bird vocalizations were being picked up in the tank and the frequency spectrum of several of these vocalizations were in the general range of the best hearing sensitivity of the California sea lion (1 kHz to 28 kHz).

Therefore, a tonal signal was chosen that was considerably higher in frequency than any known noise that could enter the tank.

In the visual acuity task, the presentation of a standard grating, consisting of 300 lines per inch (appearing as a flat gray square), was considered a catch trial, and the sea lion was required to remain silent for three seconds ("No") in order to receive one piece of herring. Presentation of variable gratings, consisting of black and white lines of much greater width, was considered a signal trial in which the sea lion was required to emit a burst of underwater clicks ("Yes") in order to receive one piece of herring. In the visual task, the sea lion was trained to remain at a fixed distance of 16 feet from the visual targets. The visual angles subtended by the stripes of the variable targets (signals) are shown in Table 1. The standard target (catch trial) and variable target (signal trial) were attached to a stimulus board that made a loud noise as a target was being lowered into the water. This noise served as a warning signal that either the variable or standard target would be presented. To ensure that the sea lion would not vocalize before the targets were completely submerged, sometimes only the stimulus board was lowered to water level. This procedure tended to minimize vocalizations to the warning signal.

In the acoustic task, a light was used as a warning signal, sometimes followed by a tone (signal trials) and sometimes not (catch trials). A single trial consisted of either the presentation of a light for 2.5 sec or the presentation of a light with a 48-kHz tone turned on during the last 0.5 sec of the 2.5-sec light duration. If a tone was presented, the sea lion was required to emit a burst of underwater clicks within 1.5 sec of tone onset ("Yes") in order to receive one piece of herring. If a tone was not presented, the sea lion had to remain silent for 3.5 sec after light onset ("no") in order to receive one piece of herring. The intensities of the acoustic signals are shown in Table 1.

Following determinations of auditory and visual acuity "thresholds" (Schusterman and Balliet, 1970; Schusterman, 1972; Schusterman et al., 1972), experiments were begun in which the a priori probability of signal presentation was varied as follows: 0.50, 0.70, and 0.30. Three different signal strengths (strong or "suprathreshold," moderate or "threshold," and weak or "subthreshold") were presented daily in a modified psychophysical method of constant stimuli. Each of the three different signal strengths was paired on a quasi-random basis from session to session with catch trials for a total of ten consecutive trials and then repeated four times within each session, for a total of 120 trials per test session. The sequence of signal strengths was such that each daily session initially went from strong to weak. Following the first block of 30 trials, each block of ten trials containing a given signal strength was presented randomly.

The 0.50 a priori probability of signal presentation was used as a constant baseline, which was returned to following the introduction and termination of each of the other two a priori probabilities. Changes in the a priori probabilities were introduced only when the sea lions had reached a relatively steady state in their rate of false alarms and hits at the constant baseline. The baseline a priori probability of 0.50 was returned to only when a relatively steady state was attained at each of the other two a priori probabilities.

Results and Discussion

Figures 1 and 2 not only show the main results on a daily basis, but also show the sequence of the a priori probabilities for both acoustic and visual conditions. Several features of these two figures are worthwhile discussing.

First, note that the hit rate with an initial signal presentation probability of 0.50 (first panel of Fig. 1) increased directly as a function of signal magnitude for both acoustic and visual conditions, and that performance in terms of hits remained relatively stable at

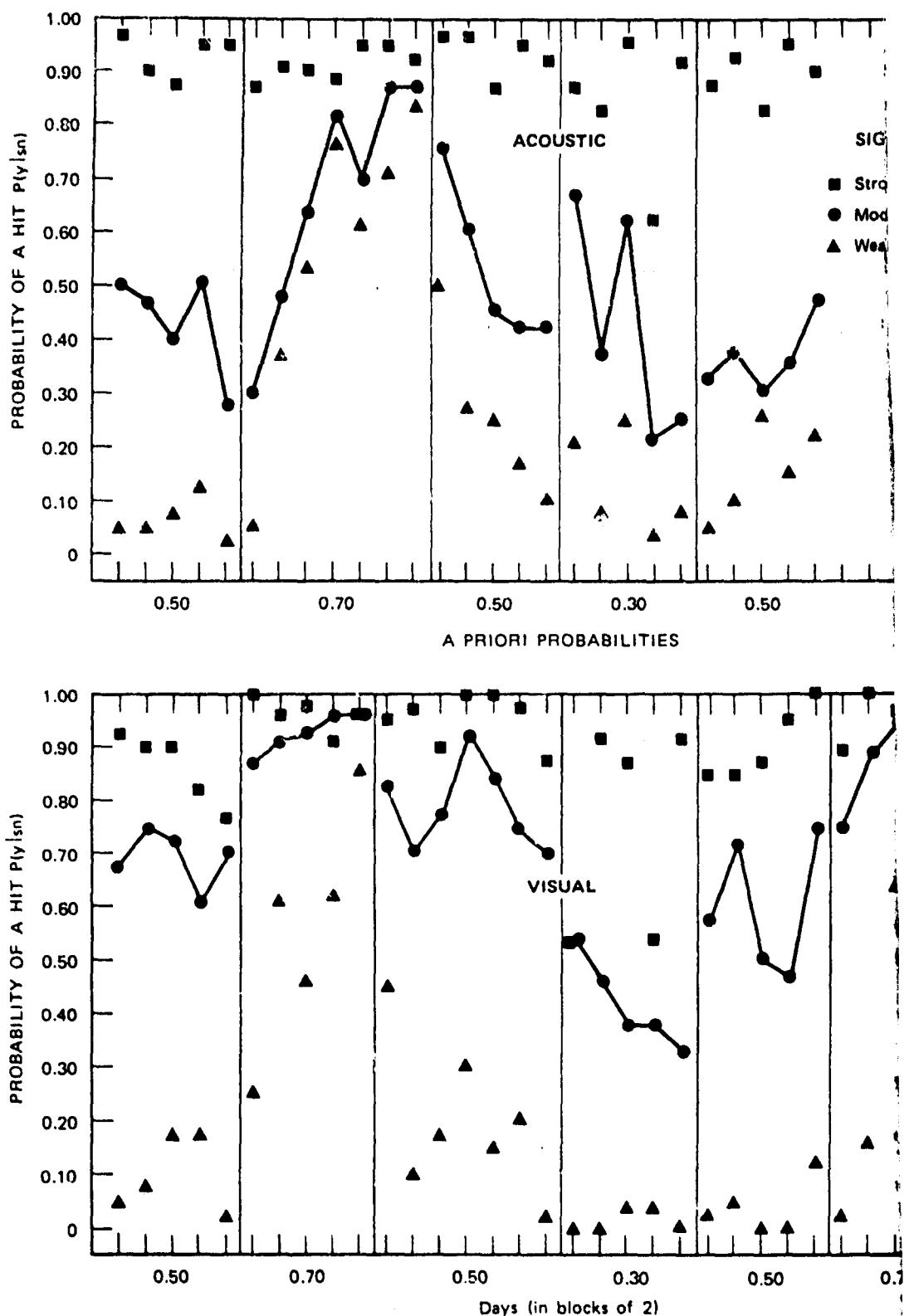


FIGURE 1 ACQUISITION OF CORRECT DETECTIONS OR HITS BY SEA LIONS AS OF SIGNAL STRENGTH AND VARIATIONS IN THE A PRIORI PROBAB

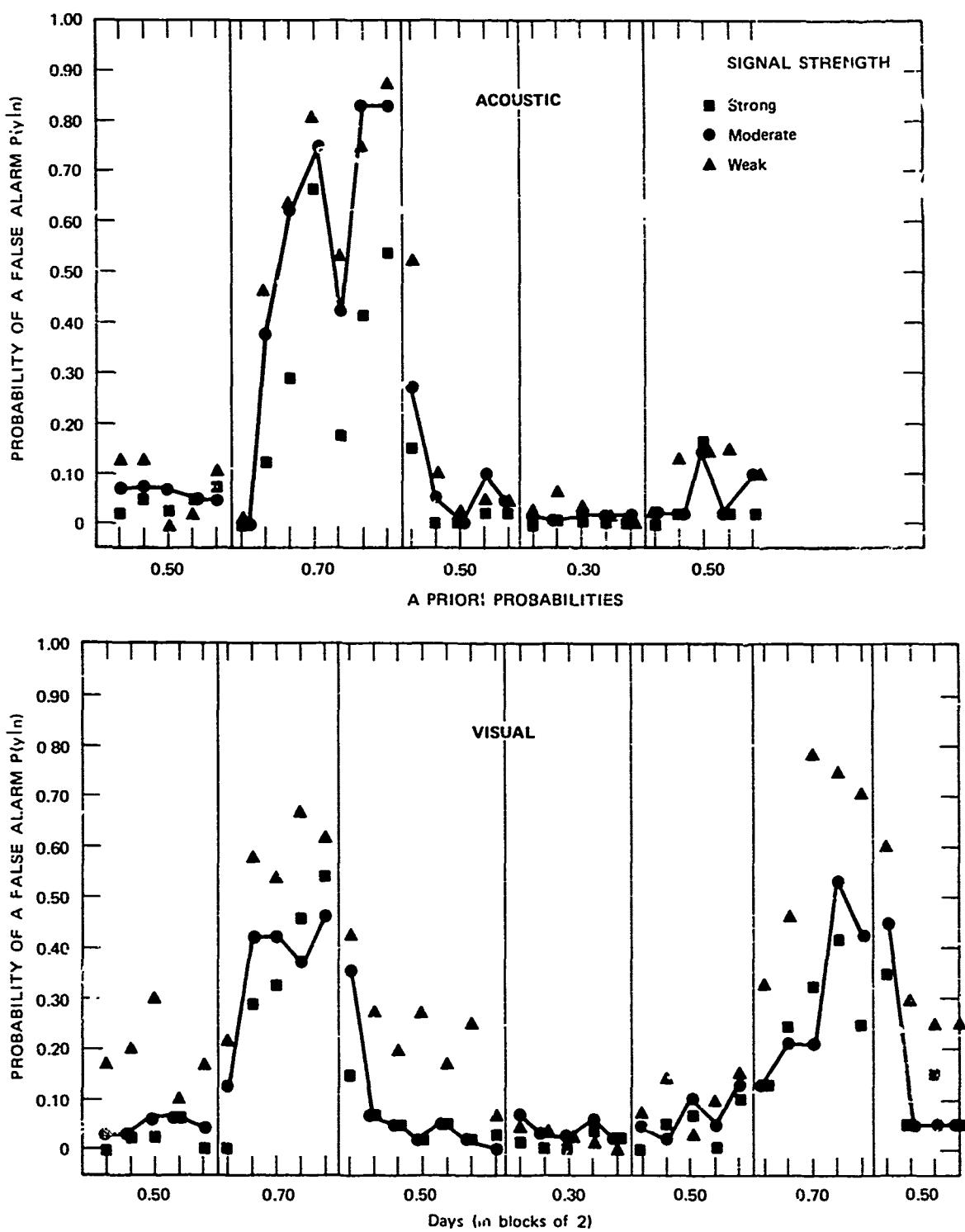


FIGURE 2 ACQUISITION OF FALSE ALARMS AS A FUNCTION OF SIGNAL STRENGTH AND VARIATIONS IN THE *A PRIORI* PROBABILITIES

each of the signal strengths over the ten-day period. One additional point to be made regarding the hit rate shown in the first panel of Fig. 1 is that the signal of "moderate" strength chosen by the experimenter for the visual task was apparently much more likely to be detected than the signal of "moderate" strength for the acoustic task. Therefore, it is difficult to make direct comparisons between the acoustic and visual tasks and, in turn, to draw any really meaningful conclusions on the basis of such comparisons. On the other hand, this difference between the two so-called moderate strength signals does allow some discussion regarding the magnitude of a signal yielding a consistent hit rate of 0.60-0.80 (visual) and the magnitude of a signal yielding a consistent hit rate of 0.30-0.50 (acoustic).

Second, note that an initial a priori probability of 0.50 results in an extremely low rate of false alarms (first panel of Fig. 2) for both acoustic and visual tasks. Except for one data point in the visual condition, the false alarm rate appeared to be consistently less than 0.20. In fact, in the acoustic condition, the sea lion kept its rate of false alarms so low and constant that signal strength played no role whatsoever in determining the false alarm rate. In the visual condition, although the false alarm rate was kept low and constant for the strong and moderate signals, the weak signal did result in a somewhat consistently higher probability of false alarms.

Another interesting finding--perhaps one of the most important features of Figures 1 and 2--is that both the hit and false alarm rates changed systematically over time when the a priori probabilities of signal presentation were varied. It should be pointed out that there was no external cue of any sort associated with a shift in the a priori probability. Therefore, the sea lions' only cues were the change in the ratio of signal to catch trials (i.e., a priori probabilities) and the payoff or reinforcement patterns associated with the consequences of responding. Generally speaking, the greatest changes from baseline (a priori probability of 0.50) detection performances occurred when the a priori probabilities were shifted to 0.70. In both acoustical and

visual conditions, shifts in the a priori probabilities had only slight effects on the hit rate when a strong signal was used, but had very significant effects on the hit rates of weak and moderate signals. Since the hit rate for the weak signals during baseline in both modalities was approximately between 0.00 and 0.20 (quite similar to the false alarm rate), the dramatic increase in hits and false alarms must be interpreted as an optimal strategy for maximizing fish reinforcements. In contrast to the negligible effects of an a priori probability of 0.70 on the hit rate of strong signals, a 0.70 probability of signal presentation significantly increased the false alarm rates of all signals, even the strongest. An a priori probability of 0.30 had some depressing effect on the hit rate of both strong and moderate signals in both modalities, and tended to reduce the false alarm probability to nearly 0.00 for signals of all magnitudes.

Finally, and quite significantly, Figures 1 and 2 clearly show that when the sea lions were returned to baseline, they performed--at least for the first two days--as if they still expected signals to be presented at probabilities of 0.70 or 0.30.

Figure 3 shows the relation between hits and false alarms during the last four days of the initial introduction of a priori probability 0.50. The data points lie between the upper left-hand corner (perfect detection) and the major diagonal (chance detection). Points lying along the minor diagonal (line drawn from the upper left-hand corner to the major diagonal) would represent no response bias, since the two possible types of "error" (false alarms and misses) would be equally likely. If bias is defined as a tendency to make one kind of error rather than another, a constant bias would be seen, independent of detectability, as a constant departure from the minor diagonal. Figure 3 clearly shows (as was pointed out in the previous graphs of daily detection performance with an a priori probability of 0.50) that as the magnitude of the signal decreased, in both the acoustic and visual conditions, the data points gradually approach the major diagonal.

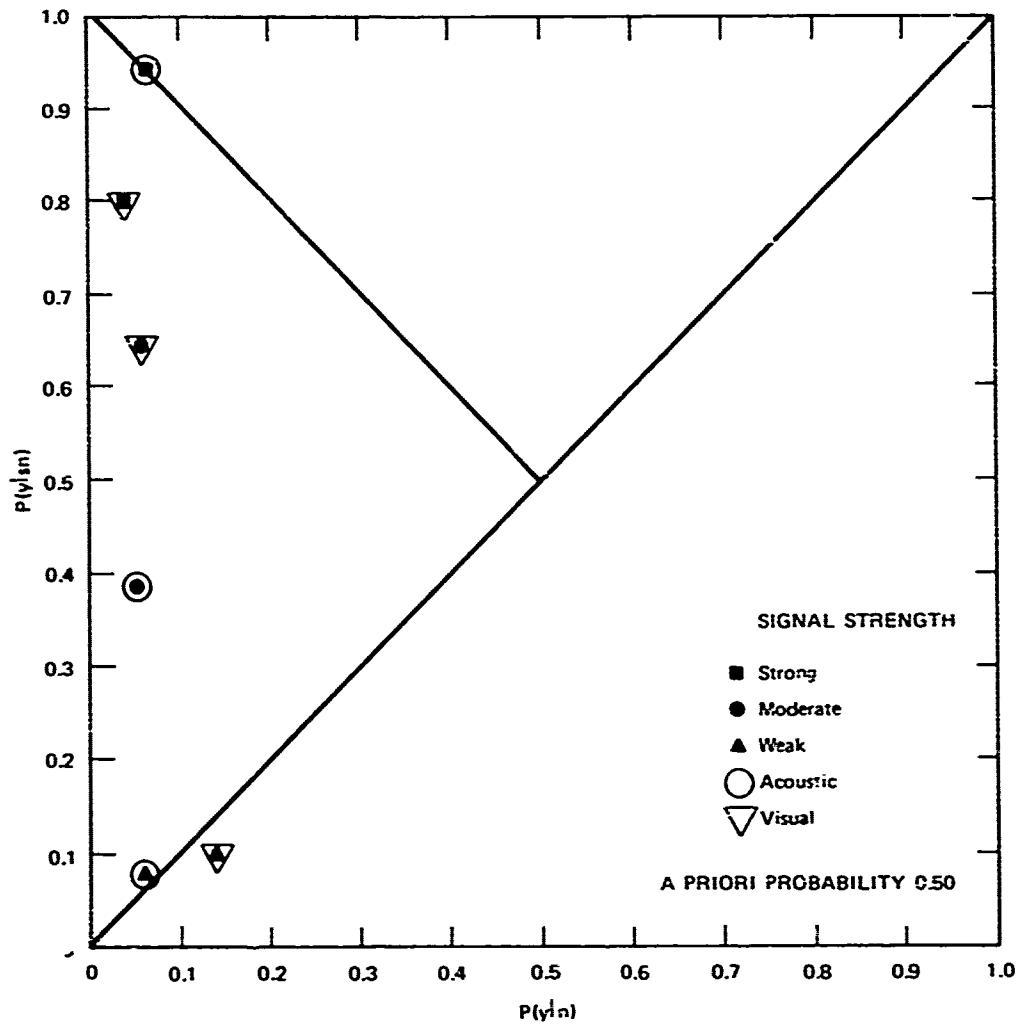


FIGURE 3 RELATIONS OF HITS TO FALSE ALARMS FOR ACOUSTIC AND VISUAL PSYCHOMETRIC FUNCTIONS

However, the points are almost parallel to the ordinate, and so represent a tendency to keep the proportion of false alarms constant at a value of approximately 0.10, regardless of the degree of detectability. A careful inspection of Figures 1 and 2 indicates that when the sea lions reached a relatively steady state performance after being returned to a 0.50 signal presentation probability from either an a priori probability of 0.30 or 0.70, the results shown in Figure 3 appear to be infinitely repeatable under the present experimental conditions. In the theory of signal detectability, it is assumed that the animal selects a criterion of signal detectability and responds "Yes" whenever the central neural effect equals or exceeds that criterion, and "No" whenever it is less (D'Amato, 1970). At the a priori probability of 0.50 (which is typically used in the laboratory for testing the underwater hearing, echolocation ability and vision of marine mammals), it would appear that the sea lions' strategy in both acoustic and visual conditions is to maximize the proportion of hits while holding the proportion of false alarms at a constant low value. Such a criterion for responding "Yes" is quite conservative and conforms to what has been called the "Neyman-Pearson objective," which will be recognized as the rationale underlying statistical tests. As was noted earlier, not only sea lions, but also seals and porpoises tested in a variety of acoustic detection tasks, including echolocation, also conform to the "Neyman-Pearson objective" (Schusterman, in preparation).

Figure 4 shows a family of ROC curves for the sea lions. All data points are based on the last four days of signal detection performance for each a priori probability (the values for 0.50 are based on all replications). The figure clearly shows that the conservative response criterion, adopted by sea lions in both acoustic and visual tasks at all levels of signal strength, can be dramatically changed by varying the a priori probability of signal presentation. For example, the visual signal (variable target) of moderate strength resulted in a hit rate that varied from about 0.35 to 0.93. The high probability of reporting the presence of the variable target is, however, associated

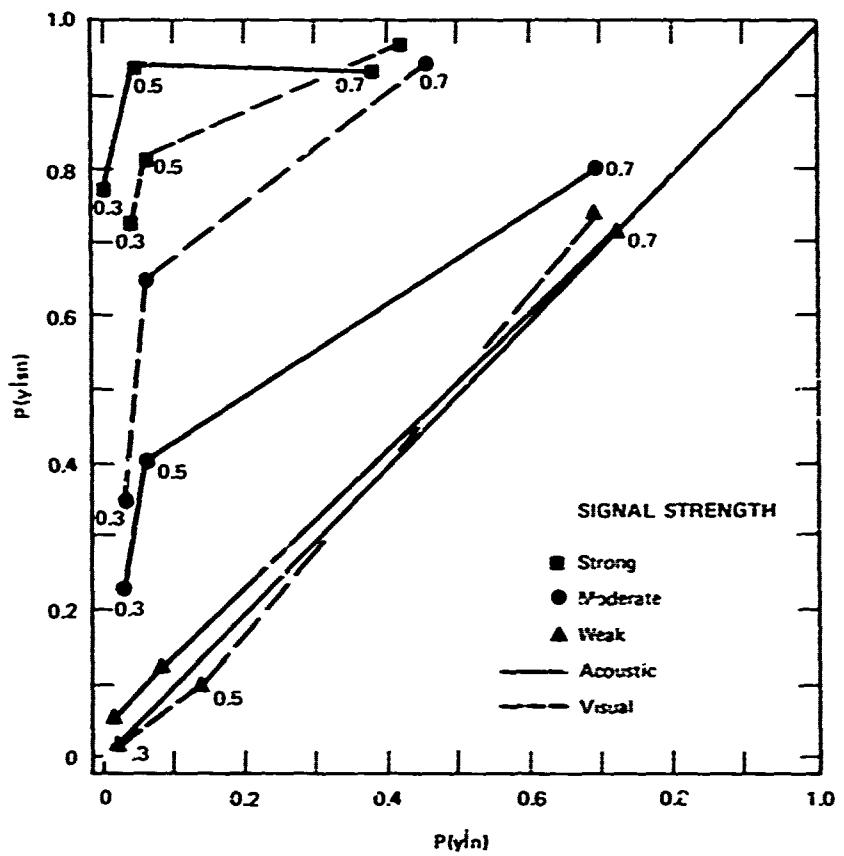


FIGURE 4 ROC CURVES FOR SEA LIONS

with a high a priori probability. If, as in classical psychophysical experiments, this variable target had been presented 70% of the time, the experimenter might have concluded that it was very easily detected. However, in our study, a target with lines of this particular width and an a priori probability of 0.70 resulted in the sea lion's reporting the presence of the variable target 45% of the time when the standard target was actually presented. This finding casts a great deal of doubt on the validity of this interpretation. A similar interpretation can be given for the acoustic task.

Note that in Figure 4, the data point representing the acoustic signal of moderate strength at an a priori probability of 0.70 is quite close to the major diagonal indicating near chance detection :bility. Thus, although under this condition the hit rate was about 0.80, the false alarm rate was almost as high--being about 0.70. This same phenomenon is reflected in the steepness and relatively high asymptotic level of the hit and false alarm curves when the sea lion in the acoustic task was shifted from an a priori probability of 0.50 to 0.70. This result suggests that the signal strength of the so-called moderate signal in the acoustic task, which at baseline (a priori = 0.50) resulted in an average hit level of approximately 0.40, may have been too weak, and at a signal presentation probability of 0.70, the sea lion not only changed its response criterion downward (i.e., became extremely liberal), but responded as if the moderate signal had been reduced in intensity. Thus, the sea lion in the acoustic task learned to ignore the so-called signal of moderate intensit- and reported the presence of signals primarily because of the reinforcement pattern associated with weak or "subthreshold" signals at an a priori probability of 0.70. The latter is the equivalent of receiving substantial reinforcement for responding "Yes" in the absence of a sig al. Presumably, the same effect was not found on the visual task because the so-called signal of moderate strength resulted in a considerably higher hit rate at an a priori probability of 0.50 (see Figures 1-4).

Table 1 describes d' or sensitivity index as a function of signal strength and a priori probabilities. These data essentially support the description of Figure 4, i.e., although the variation of signal presentation probability changed the response criterion in both tasks and at all signal intensity levels, only in the visual task did the sensitivity of the sea lion remain relatively stable, whereas in the acoustic task, sensitivity was decreased when the animal was presented with an a priori signal probability of 0.70. Figure 5 shows that in the acoustic condition, d' decreased to almost 0.00 following the first two days of the sea lion's shift from an a priori probability of 0.50 to 0.70. The figure also shows the stability of d' over days for an a priori probability of 0.50 in the acoustic task and for 0.50 and 0.70 in the visual task.

Since the theory of signal detectability is usually confined to situations where signal strength is kept constant, the fact that we found relative invariance of sensory sensitivity in a visual task, but not in an acoustic task, with sea lions suggests that the theory can be successfully applied, at least in some cases, even when signal strength covaries with the a priori probability variable.

Figures 1 and 2 suggest that during both the acoustic and the visual task, each sea lion, on returning to baseline, still responded to some degree on the basis of its previous experience with the two other signal presentation probabilities. For this reason, another estimate of ROC curves for sea lions was based on signal detection performance following the sea lions' initial return (first two days) to the constant baseline signal presentation probability of 0.50. The results are shown in Figure 6. Table 2 presents the d' values associated with the data plotted in Figure 6.

According to signal detectability theory, the data points of Figure 6, when plotted on double-probability paper with response probabilities transformed into Z units, should yield a straight line with

Table 1

Values* of d' (sensitivity) as a function of the a priori probability of the signal's appearance, the strength of signal, and whether the signal was acoustical or visual

<u>Signal Strength</u>	<u>dB re 1 μB (in water)</u>	Values of d' at <u>a Priori Probabilities</u>		
		<u>0.30</u>	<u>0.50</u>	<u>0.70</u>
<u>Acoustic</u>				
Strong	+36	3.05	3.19	1.87
Moderate	+30	1.31	1.36	0.38
Weak	+26	0.77	0.11	0.30
<u>Visual</u>				
<u>Visual Angle (minutes)</u>				
Strong	7.3	2.49	2.60	2.08
Moderate	6.1	1.42	1.94	1.77
Weak	4.4	0.27	-0.20	0.17

* All values are based on the last four days of signal detection performance for each condition.

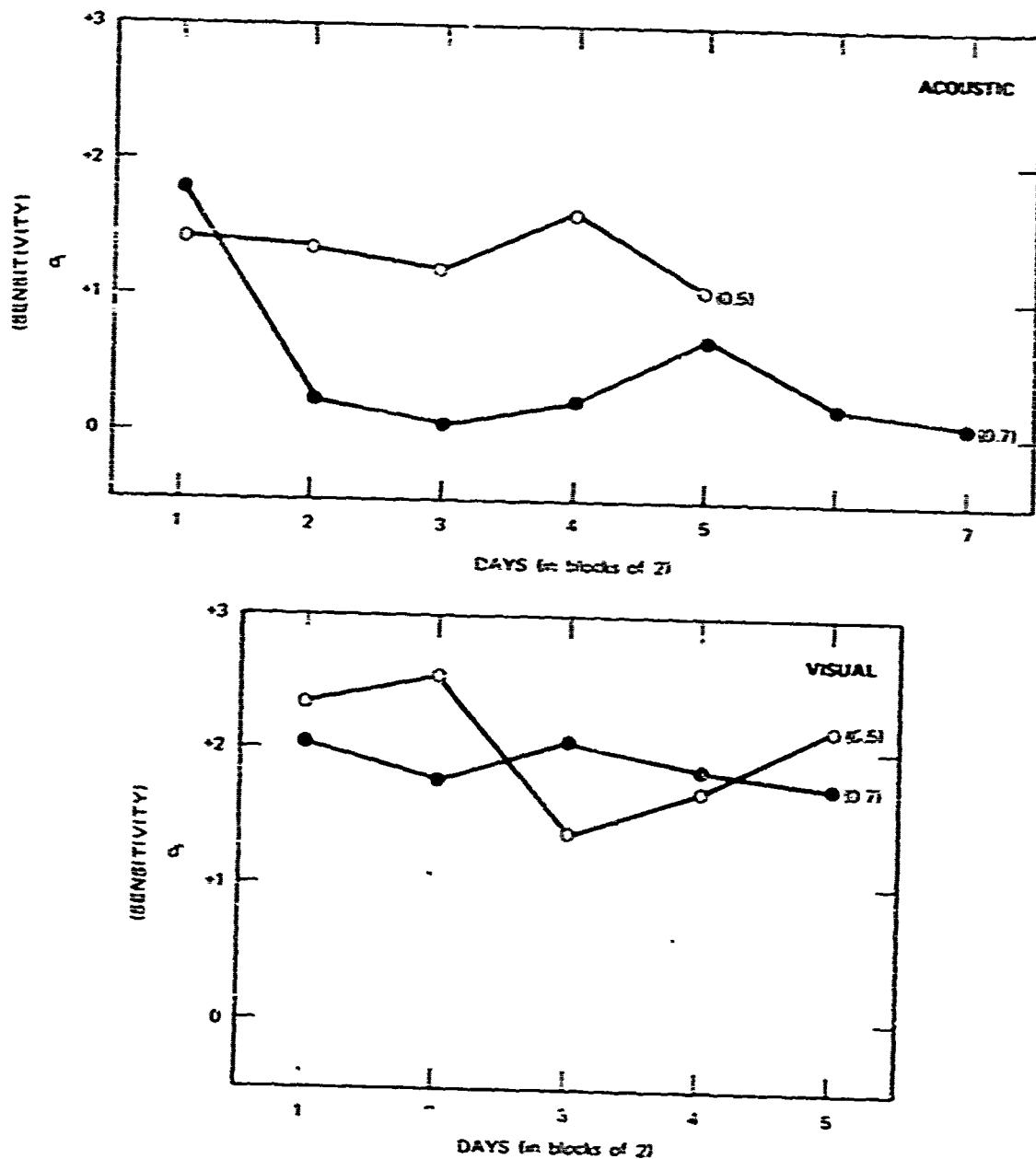
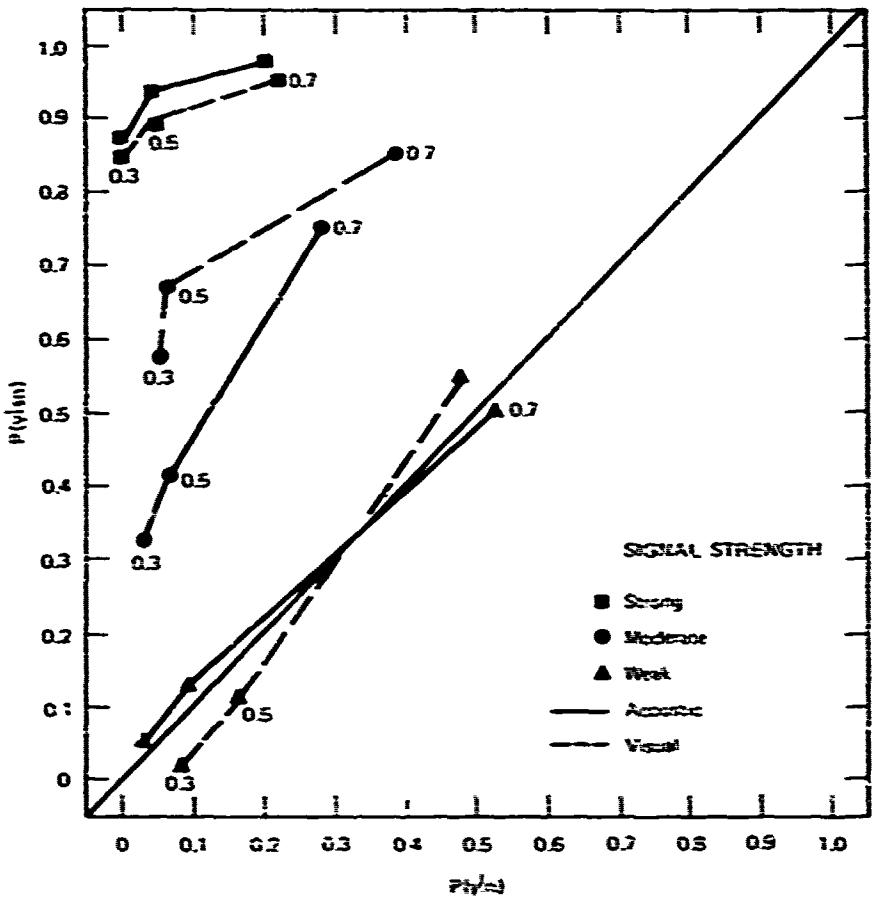


FIGURE 5 CHANGES IN d' OVER DAYS WITH A PRIORI PROBABILITIES AS A PARAMETER



ROC CURVES FOR SEA LIONS BASED ON INITIAL DETECTION PERFORMANCES AFTER THE ANIMALS HAVE BEEN RETURNED TO A SIGNAL PRESENTATION PROBABILITY OF 0.50.

Table 2

Values of d' (sensitivity)*

<u>Signal Strength</u>		<u>Values of d' at a Priori Probabilities</u>			
		<u>0.30</u>	<u>0.50</u>	<u>0.70</u>	
<u>Acoustic</u>					
<u>$\text{dB re } 1 \mu\text{S (in water)}$</u>					
Strong	+36	3.50	3.30	3.09	
Moderate	+30	1.44	1.32	1.27	
Weak	+26	0.34	0.27	-0.08	
<u>Visual</u>					
<u>Visual Angle (minutes)</u>					
Strong	7.3	3.36	2.92	2.41	
Moderate	6.1	1.83	1.99	1.34	
Weak	4.4	-0.41	-0.16	0.18	

* The table is arranged similarly to Table 1, except that all d' values for a priori signal presentations of 0.30 and 0.70 are based on signal detection performance following the sea lions' initial return (first 2 days) to the constant baseline signal presentation probability of 0.50. The d' values of 0.50 are based on combined detection performances during the last four days of each constant baseline.

a slope of 1.0 (Green and Sæts, 1966). Figure 7 shows that for all cases, the functions are quite close to linearity and the slopes do approximate 1.0.

Brief Summary and Conclusions

Underwater signal-detection performance of sea lions was influenced by changes in the probability of signal presentation in both acoustic and visual tasks. Normally, marine mammals in a signal-detection task maintain a low level of false alarms while attempting to maximize their correct detections or hits. In the present series of experiments, it was shown that such an objective in a marine mammal (the California sea lion) can be changed without, in some instances, changing the animal's sensitivity. Thus, by changing its response criterion as a function of varying the probability of signal presentation, a set of probability limits could be induced into a sea lion regarding the acceptance or rejection of signal presence or signal difference. By relating the probability of hits to false alarms for several signals of varying magnitude, one can plot the "receiver-operating-characteristic" (ROC) curves for sea lions.

Without knowledge of an ROC curve, it is unsafe to assume that the ratio of signal trials to catch trials should be any less than 5:5 (a priori probability = 0.50) when testing the sensitivity of a marine mammal. In addition, it is imperative to take into consideration not only correct reports of a signal's presence (hits), but also the rate of false alarms.

SPECIAL PARTICIPATION IN NAVAL PROGRAMS

During the course of this contract, Dr. Schusterman, in addition to giving a series of lectures to members of the Ocean Sciences Division of Navy Undersea Research and Development Laboratories in Hawaii, also participated in the Naval Research Advisory Committee Ad Hoc Group on

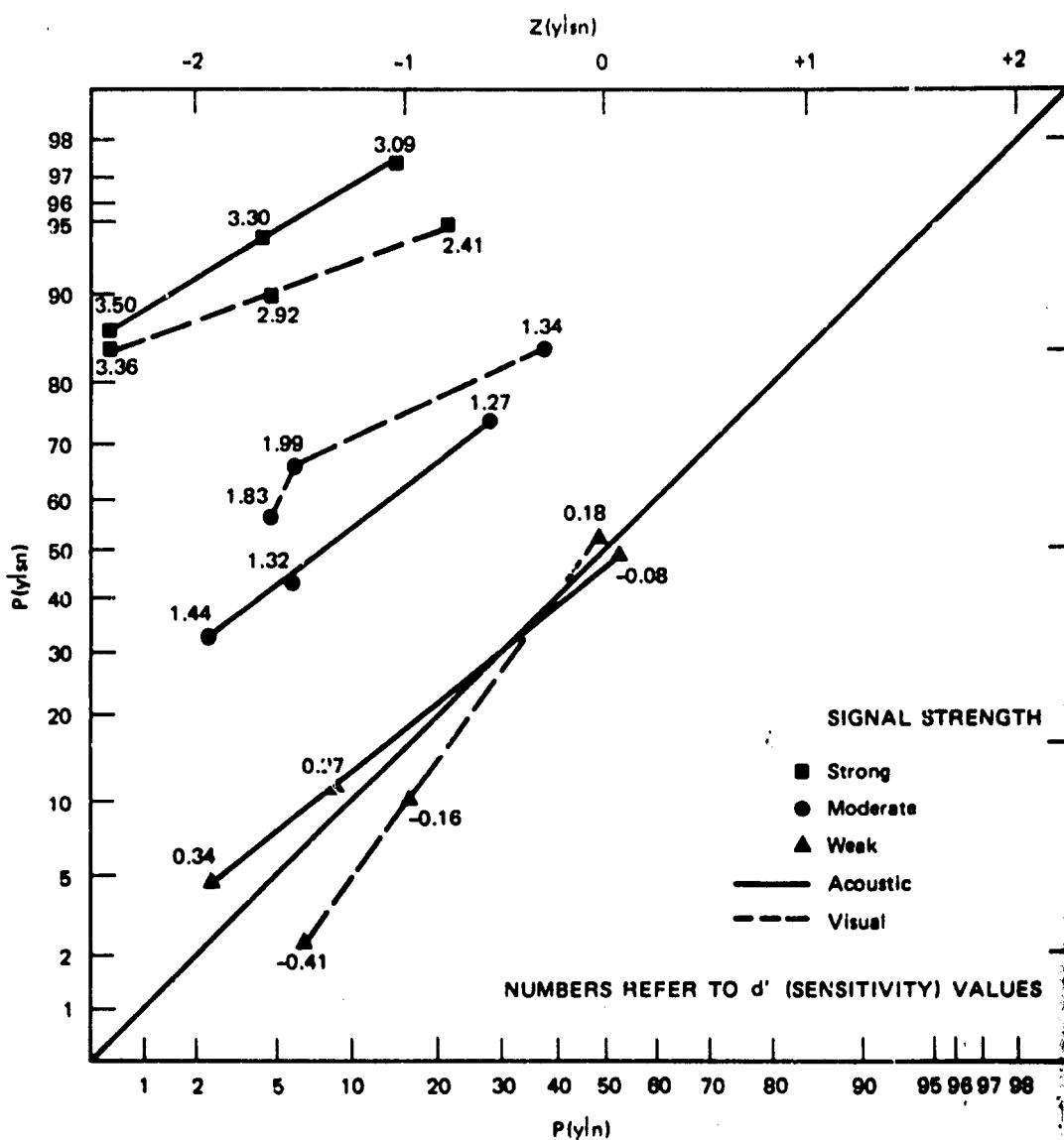


FIGURE 7 NORMALIZED ROC CURVES OF FIGURE 6. Two of the axes are marked off in Z scores.

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Marine Mammal Research and Development. The mission of this committee was to assess the scientific aspects of the ongoing programs and to make recommendations for their improvement.

PLANS FOR THE FUTURE

We will continue to systematically explore some of the variables affecting the detection of underwater acoustic and visual signals by sea lions and other aquatic mammals. These variables will include: (a) sequence of signal presentation, (b) payoff matrix or magnitude of reward, (c) schedules of reinforcement, and (d) combinations of these variables. In other experiments, sea lions will be shifted from one task to another to determine the degree to which visual decision-making transfers to auditory decision-making and vice versa. We also plan to make a detailed analysis of the results of previously reported acoustic detection experiments with cetaceans and pinnipeds in order to provide a means of evaluating the separate contributions to the detection performance of a marine mammal's sensitivity and its response criterion. This work will be continued at the Ecological Field Station at California State University, Hayward, California.

CURRENT PUBLICATIONS

Schusterman, R. J., Balliet, R. F., and Nixon, J. (1972). Underwater audiogram of the California sea lion by the conditioned vocalization technique. *J. Exp. Anal. Behav.* 16, 147-158.

Schusterman, R. J. (1972). Visual acuity in pinnipeds. In H. E. Winn and B. L. Olla (Eds.), Behavior of Marine Animals: Recent Advances. New York: Plenum Press.

Schusterman, R. J. (in press). Pinniped sensory perception. In K. Ronald and A. W. Mansfield (Eds.), The Biology of the Seal. London: Academic Press.

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